

# $\text{H}_2\text{D}^+$ : a light on baryonic dark matter?

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## ABSTRACT

It has been suggested that the dark halos of galaxies are constituted by cloudlets of cold ( $\leq 10$  K)  $\text{H}_2$  and dense ( $\geq 10^7 \text{ cm}^{-3}$ ) molecular gas. Such gas is extremely difficult to detect, because the classical tracers of molecular gas, CO and/or dust grains, have very low abundances and their emission is exceedingly weak. For this reason, the cloudlet hypothesis remains so far substantially unproven. In this Letter we propose a new method to probe the presence of cold  $\text{H}_2$  clouds in galactic halos: the ground transition of ortho- $\text{H}_2\text{D}^+$  at 372 GHz. We discuss why the  $\text{H}_2\text{D}^+$  is abundant under the physical conditions appropriate for the cloudlets, and present a chemical model that predicts the  $\text{H}_2\text{D}^+$  abundance as function of four key parameters: gas density and metallicity, cosmic ray ionization rate and dust grain size. We conclude that current ground-based instruments might detect the ortho- $\text{H}_2\text{D}^+$  line emitted by the cloudlets halo, and prove, therefore, the existence of large quantities of dark baryonic matter around galaxies.

*Subject headings:* Cosmology - Dark matter

## 1. Introduction

One of the most astounding results of modern cosmology is the fact that we currently firmly understand the nature of but a tiny fraction of the matter content of the universe: the “luminous matter” constituting the stars and gas in galaxies. This component amounts to only  $\sim 0.3\%$  of the mass (Fukugita & Peebles 2004). The largest fraction of cosmic matter belongs to the so-called “dark sector” (95.4%), split into dark energy (72%) and dark matter (23%). In total,  $\sim 4.5\%$  of the universe matter is present in the form of baryonic matter.

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However, stars account for only  $\sim 5\%$  of it. A significant fraction of the remaining 95% is thought to constitute the warm/hot intergalactic gas traced by the Ly $\alpha$  forest (Savage et al. 2002; Penton et al. 2004; Richter et al. 2006) and/or X-rays (Cen & Ostriker 1999; Nicastro et al. 2005; Williams et al. 2006). However, the numbers are uncertain and up to 50% of the baryons at low redshift may still be unaccounted for.

In galaxies, the evidence that most of the mass is *not* contained in the stellar or any other observed component stems from the study of rotation curves, derived from stellar light and HI gas emission (Rubin et al. 1962; Prugniel et al. 1998), which indicate the presence of a large invisible mass surrounding the galaxies. The nature of these dark matter halos has long baffled astronomers. It cannot be *diffuse* baryonic matter, because both neutral or molecular gas would be detected in one way or another. For this reason, it has been proposed that it may be non-baryonic in nature. However, the amount of dark mass in galaxies could be as large as the amount needed in the form of baryons in order to fulfill the constraints from Big Bang nucleosynthesis (Kirkman et al. 2003). Besides, there are other reasons to assume that the dark matter in galaxies may be mostly baryonic (Pfenniger et al. 1994; Pfenniger & Combes 1994; Gerhard & Silk 1996). An invisible baryonic form would be condensed objects, like brown dwarfs or massive compact halo objects (MACHOS), but they both have now been ruled out as significant contributors (Alcock et al. 2001). Another possibility is that baryonic dark matter is present in the form of cold ( $\leq 10\text{K}$ ), molecular clouds, also called “cloudlets” (Pfenniger et al. 1994; Pfenniger & Combes 1994). There is considerable discussion in the literature about the allowed range of parameters for such clouds, and the values obtained depend on the particular model and physical constraints used. Gerhard & Silk (1996) consider both the collisional cross section of clouds and the thermal stability against collapse and conclude that the clouds should be colder than 10 K, have masses around  $1 M_{\odot}$  and column densities above  $1 \times 10^{23} \text{ cm}^{-2}$ . Walker & Wardle (1998) suggest that such clouds can be responsible for radio scintillations observed toward quasars and derive that the clouds should be a few AU in size and have masses below  $10^{-3} M_{\odot}$ . Wardle & Walker (1999) consider the thermal stability of such clouds against evaporation and find a lower limit for the mass of  $\sim 10^{-6} M_{\odot}$  to keep the clouds stable in the current epoch (low redshift). All these estimates involve uncertain parameters like the cosmic ray ionization rate in the halo. Rafikov & Draine (2001) use constraints from micro-lensing studies to derive a lower limit of the cloud masses of  $\sim 10^{-5} M_{\odot}$  and conclude that models with the Walker and Wardle parameters of  $10^{-3} M_{\odot}$  and about 10 AU radii are still acceptable within the current observational limits. Kalberla et al. (1999) and Ohishi et al. (2004) suggest small halo cloudlets of 6AU and masses of  $10^{-3} M_{\odot}$  as the explanation for the unidentified EGRET sources. It is, however, not clear if these clouds exist in a stable form, or if they are simply the highest density component of a fractal distribution of cold

molecular gas. In summary, several authors have invoked the possibility that a substantial amount of baryonic mass is in cold cloudlets, but the uncertainty in the involved physics is so large that so far no consensus exists on the mass and size of the presumed cloudlets. Heithausen (2004) tried to probe the cloudlets in our own galaxy by means of high angular resolution CO observations. He indeed detected clumps of molecular material at 7-18 K, but it is unclear what their masses, sizes and densities are, given the uncertainty on the distance and CO abundance (see §2). In addition, Lawrence (2001) discusses the possibility that some faint SCUBA sources are in fact local very low temperature dust clouds, with characteristics similar to the halo cloudlets.

In this Letter, we assume that the galactic dark halos are constituted of such cloudlets, without further discussing the detailed structure and stability of such objects. Instead, we propose a new method to test this hypothesis: observations of the ground state transition of the ortho- $\text{H}_2\text{D}^+$ .

## 2. Why $\text{H}_2\text{D}^+$

Low metallicity cold molecular gas is intrinsically difficult to detect. The main constituent of cold gas,  $\text{H}_2$ , does not have a permanent dipole moment and its ground transition can only be excited in warm ( $> 100\text{K}$ ) gas. The most sensitive probes of “standard” molecular clouds in the galactic disk are dust continuum emission and CO millimeter line emission. However, if the gas is primordial (i.e. not enriched with the products of stellar nucleosynthesis) or very low in metallicity, the dust abundance is zero or very low and its emission undetectable. The same argument holds for CO. Even if the metallicity is non-zero and a small amount of CO and dust were present, the CO molecules would quickly freeze-out onto dust grains and in this way still escape detection. Similar chemical conditions can actually be found in particularly cold objects of our Galaxy: prestellar cores and protoplanetary disks, which contain regions so cold and dense, that CO and other heavy-element bearing molecules freeze out onto the cold grains. While galactic matter is still traceable through dust emission, the severe depletion of CO from the gas phase causes these regions to become “invisible” in terms of molecular emission, just like the presumed cloudlets in the dark galactic halos. However, recent breakthroughs in the observation and theoretical understanding of *molecular deuteration* have opened new ways to probe cold and CO depleted regions: the ground transition of  $\text{H}_2\text{D}^+$  at 372 GHz, which is indeed a very specific signature of extremely cold and dense regions. As a matter of fact, the detection of this line has been sought after for decades in galactic giant molecular clouds (whose mass is  $\geq 10^4 M_\odot$ ) without success (van Dishoeck et al. 1992), whereas it is easily detected in the small ( $\leq 1 M_\odot$ ) but cold and

dense pre-stellar cores (Caselli et al. 2003) and/or proto-planetary disks (Ceccarelli et al. 2004). The initially unexpected presence of deuterated molecules in large abundances (Ceccarelli 2004) has now been explained by a new class of chemical models (Roberts et al. 2003). It is precisely the disappearance of the CO from the gas phase that is causing a dramatic enhancement of  $\text{H}_2\text{D}^+$ ,  $\text{HD}_2^+$  and  $\text{D}_3^+$  with respect to  $\text{H}_3^+$  (for details see § 3). Excitingly,  $\text{H}_2\text{D}^+$  and  $\text{HD}_2^+$  *do* have ground transitions observable with ground-based sub-millimeter telescopes (Stark et al. 1999; Vastel et al. 2004). These transitions can be used to probe the presence of the hypothetical cloudlets forming the baryonic dark matter.

### 3. Model Description

The chemical model we are using is largely identical with the one described by Ceccarelli & Dominik (2005), which is based upon work by Roberts et al. (2003) and Walmsley et al. (2004). We summarize here the basic assumptions entering into this model, and the modifications we added to meet the requirement of cold gas clouds in galactic halos. In cold and dense gas, the most abundant molecule is always  $\text{H}_2$ . HD is present as well, and generally is the main reservoir of deuterium, with an abundance of  $3 \times 10^{-5}$  relative to  $\text{H}_2$  (Linsky 2003). At low temperature, chemistry is generally driven by ion-neutral reactions, and therefore, by the process of ionization due to cosmic rays. Cosmic rays ionize  $\text{H}_2$  and quickly lead to the formation of  $\text{H}_3^+$ , which is the main charge carrier in the gas.  $\text{H}_3^+$  is destroyed by reactions with grains, heavy element bearing molecules like CO and  $\text{N}_2$  and, at a very low rate, through direct recombination with electrons. It also reacts with HD, and this is the starting point of deuterium enrichment chemistry whose overwhelming importance has only recently been recognized.  $\text{H}_3^+$  reacts with HD to form  $\text{H}_2\text{D}^+$ .



The reaction is endothermic, i.e. the reverse reaction  $\text{H}_2\text{D}^+ + \text{H}_2 \rightarrow \text{H}_3^+ + \text{HD}$  is practically forbidden at temperatures below  $\sim 30$  K. Therefore, a deuterium atom captured in this way into an  $\text{H}_3^+$  isotopologue remains there until it is returned by a reaction neutralizing the ion. The relevant reactions are those with dust grains, CO and  $\text{N}_2$  molecules, and direct recombinations with electrons. As in cold and/or metal-poor environments the abundance of those species is low,  $\text{H}_2\text{D}^+$  tends to include the *entire positive charge*. Of course,  $\text{H}_2\text{D}^+$  can itself react with HD to form  $\text{HD}_2^+$ , and a further step leads to  $\text{D}_3^+$ .

Therefore, in cold gas, the positive charge is distributed between  $\text{H}_3^+$ ,  $\text{H}_2\text{D}^+$ ,  $\text{HD}_2^+$ , and  $\text{D}_3^+$  (Roberts et al. 2003; Walmsley et al. 2004). It turns out that, at extremely low metallicities, this no longer holds. Under “normal” galactic conditions,  $\text{H}^+$  is quickly destroyed

by recombination on dust grain surfaces. At the lower grain abundances characteristic of low metallicity conditions, the only destruction channel for  $\text{H}^+$  is direct recombination with electrons, a very inefficient reaction. Therefore,  $\text{H}^+$  can dominate the positive charge. In the case where  $\text{H}^+$  dominates, the ionization balance can be calculated ignoring the presence of  $\text{H}_3^+$  and solving the equation

$$x_{\text{H}^+}^2 n_{\text{H}_2} k_{\text{pe}} + 2[\text{D}] x_{\text{H}^+}^2 n_{\text{H}_2} k_{\text{pHD}} - \xi_{\text{cr}} = 0 \quad (2)$$

where  $x_{\text{H}^+}$  is the  $\text{H}^+$  abundance with respect to  $\text{H}_2$ ,  $n_{\text{H}_2}$  is the  $\text{H}_2$  density,  $[\text{D}]$  is the elemental deuterium abundance,  $\xi_{\text{cr}}$  is the cosmic ray ionization rate,  $k_{\text{pe}}$  and  $k_{\text{pHD}}$  are the reaction rates of  $\text{H}^+$  recombination with electrons ( $3.6 \times 10^{-12} (T_{\text{gas}}/300\text{K})^{-3/4} \text{ cm}^3 \text{ s}^{-1}$ ; Millar et al. (1997)) and HD ( $2.0 \times 10^{-9} \exp[-464/T_{\text{gas}}] \text{ cm}^3 \text{ s}^{-1}$ ) respectively. In the case where  $\text{H}_3^+$  and its deuterated isotopologues dominate the positive charge, the electron abundance is found by solving Eq. 13 of Ceccarelli & Dominik (2005). The low metallicity in primordial gas also affects directly the abundances of CO,  $\text{N}_2$  and dust grains. In the present model, the abundance of the grains  $x_{\text{gr}}$  is scaled with a factor  $Z/Z_{\text{sun}}$  denoting the metallicity of the material relative to solar abundances. In the same way, we scale the abundances of CO and  $\text{N}_2$  linearly with the metallicity.

#### 4. Discussion and Conclusions

Figure 1 shows the chemical composition of the cloudlets as function of four key parameters: the density in the cloud  $n_{\text{H}_2}$ , the metallicity  $Z$ , the cosmic ray ionization rate applicable in the halo,  $\xi_{\text{cr}}$ , and the size of dust grains present in the clouds,  $a_{\text{gr}}$ . The plots show that  $\text{H}_2\text{D}^+$  is almost never the main positive charge carrier in the cloudlets, even though it is almost always more abundant than  $\text{H}_3^+$ . The conditions are so extreme in the cloudlets that either  $\text{D}_3^+$  or  $\text{H}^+$  are the most abundant ions. As these are not observable,  $\text{H}_2\text{D}^+$  remains the best tracer. It is very instructive to study the dependence of the  $\text{H}_2\text{D}^+$  abundance on the different parameters. First of all, the abundance decreases as the density increases, leading to a weak dependence of the total  $\text{H}_2\text{D}^+$  column density in a cloud on the cloudlet density. This also means that the internal structure of the cloudlets only weakly influences the resulting column densities. Also the dependence on the metallicity of the clouds is shallow. Changing it from  $10^{-3}$  times solar to solar increases the abundance of  $\text{H}_2\text{D}^+$  by just a factor of 30. The abundance of all ions scales approximately with cosmic ionization rate  $\sqrt{\xi_{\text{cr}}}$ . Finally, the size of grains plays an important role. The  $\text{H}_2\text{D}^+$  abundance is highest for the smallest grain sizes. As the grains get bigger, the  $\text{H}_2\text{D}^+$  abundance decreases but levels out at grain sizes of  $0.1 \mu\text{m}$ . It should be kept in mind that the dependences discussed here are all relative to the chosen set of parameters. In reality, the parameter space is four dimensional and the

dependencies are complex. However, we can derive a range of abundances to be expected in the cloudlets. The  $\text{H}_2\text{D}^+$  abundance is between  $10^{-7}$  and  $10^{-12}$ , when taking into account a large range for the four parameters varied simultaneously (larger than what is shown in Fig. 1).

The emission from the ground state transition of ortho- $\text{H}_2\text{D}^+$  at 372 GHz can be used to observationally probe cold halo cloudlets. Like any other emission line, the ortho- $\text{H}_2\text{D}^+$  line intensity depends on the excitation conditions (gas temperature and density), and on the average column density of ortho- $\text{H}_2\text{D}^+$  in the telescope beam. Since the critical density of the ortho- $\text{H}_2\text{D}^+$  ground transition is  $\sim 10^6 \text{ cm}^{-3}$ , the line is very likely always thermally populated. In addition, the cloudlets temperature is likely lower than 10 K but larger than  $\sim 5$  K (the condensation temperature for  $\text{H}_2$ ), so that the intensity very weakly (less than a factor 4) depends on the temperature. Therefore, the most important parameter in the prediction of the  $\text{H}_2\text{D}^+$  line intensity is the ortho- $\text{H}_2\text{D}^+$  column density, which depends on the ortho-to-para ratio and the total  $\text{H}_2\text{D}^+$  column density.

*a)  $\text{H}_2\text{D}^+$  ortho-to-para ratio:* The chemical model gives the total abundance of  $\text{H}_2\text{D}^+$ . Theoretical estimates predict that for large ( $\geq 10^6 \text{ cm}^{-3}$ ) densities this ratio depends only on the gas temperature and reaches the unity at 9 K Flower et al. (2004). However, these theoretical estimates strongly depend on the ortho-to-para ratio of  $\text{H}_2$ , itself a very poorly known (=observed) parameter. For the purpose of estimating the detectability of the ortho- $\text{H}_2\text{D}^+$  line at 372 GHz, we will consider an ortho-to-para ratio about unity.

*b)  $\text{H}_2\text{D}^+$  column density:* We assume that the halo contains a mass  $M_h$  in a sphere with radius  $R_h$ . The average  $\text{H}_2$  column density through this halo can be estimated to be  $N_{\text{H}_2, h} = M_h / \pi R_h^2 \mu m_p$  where  $\mu = 2.8$  is the mean molecular weight in  $\text{H}_2$  gas and  $m_p$  is the mass of a proton. Note that this column is an average of lines of sight passing through a cloudlet, and other lines of sight not passing through one. In an uniformly distributed halo, the average column density of  $\text{H}_2\text{D}^+$  is then simply given by

$$N_{\text{H}_2\text{D}^+, h} = \frac{M_h}{\pi \mu m_p R_h^2} x_{\text{H}_2\text{D}^+}(n_{\text{H}_2}, Z, \xi_{\text{cr}}, a_{\text{gr}}) \quad (3)$$

where  $x_{\text{H}_2\text{D}^+}$  is the abundance of the  $\text{H}_2\text{D}^+$  molecule relative to  $\text{H}_2$ . We will use the example of NGC3198 to have a guideline for the choice of general halo properties. This galaxy is considered the prototype for studies of halo dark matter. Interpretation of the HI rotational curve indicates that the halo extends more than 30 kpc, and the mass contained within 30 kpc is  $1.5 \times 10^{11} M_\odot$  (van Albada et al. 1985). If this mass is present as cold  $\text{H}_2$  clouds, it corresponds to an average total column  $N_{\text{H}_2, h} = 3 \times 10^{21} \text{ cm}^{-2}$ . Using the results of the chemical modeling above, we arrive at an estimated column density of  $\text{H}_2\text{D}^+$  between  $3 \times 10^9$  and  $3 \times 10^{13} \text{ cm}^{-2}$ .

*c) ortho-H<sub>2</sub>D<sup>+</sup> line emission:* If the ortho-H<sub>2</sub>D<sup>+</sup> line is optically thin for an individual cloudlet, the line emission is simply proportional to the column density given above. If the line is optically thick, the emission is proportional to the column density at which the line becomes optically thick multiplied by the telescope filling factor. To have an order of magnitude, the ortho-H<sub>2</sub>D<sup>+</sup> line becomes optically thick at an ortho-H<sub>2</sub>D<sup>+</sup> column density of  $\sim 10^{13}$ , if the linewidth is  $\sim 1$  km/s. Therefore, the line emission depends on the properties of individual cloudlets, which are very different depending on the particular model used (see §1). In the following, we will consider two cases.

The first one assumes a cloudlet mass of  $1M_{\odot}$  and a radius of 1000 AU (Gerhard & Silk 1996), corresponding to  $n_{H_2} \sim 6 \times 10^7 \text{ cm}^{-3}$  and an average cloud  $N_{H_2} \sim 1.3 \times 10^{24} \text{ cm}^{-2}$ . Using a line width of 2 km/s (twice the virial velocity of a single cloud), an abundance of  $x(\text{H}_2\text{D}^+) \sim 3 \times 10^{-11}$  is the limit for optically thin emission. For the case of NGC3198, the filling factor of such clouds would be  $4 \times 10^{-3}$  when we assume a constant density of cloudlets throughout the halo. Thus, the maximum average ortho-H<sub>2</sub>D<sup>+</sup> column density of the halo is  $\sim 10^{11} \text{ cm}^{-2}$ . For the second case, the least favorable to a H<sub>2</sub>D<sup>+</sup> detection, we use the unidentified EGRET sources which should have masses of  $10^{-3} M_{\odot}$  and radii of 10 AU. In this case, the cloudlet  $n_{H_2}$  reaches  $6 \times 10^{10} \text{ cm}^{-3}$  and the  $N_{H_2}$  of such a cloudlet would be  $2 \times 10^{25} \text{ cm}^{-2}$ . The ortho-H<sub>2</sub>D<sup>+</sup> line would be optically thick within the cloudlet for  $x(\text{H}_2\text{D}^+) > 1.5 \times 10^{-12}$  (assuming that the linewidth is dominated by a 0.5 km/s turbulence). For an uniform dark halo mass and size like in NGC3198, this case corresponds to a filling factor of  $4 \times 10^{-4}$ , and, therefore, a maximum average ortho-H<sub>2</sub>D<sup>+</sup> column density of  $\sim 10^{10} \text{ cm}^{-2}$ .

Note that a centrally condensed distribution of the cloudlets could increase the filling factor and/or the average H<sub>2</sub>D<sup>+</sup> column density close to the galaxy center significantly in both cases. For example, if the cloudlets follow a  $r^{-1}$  or  $r^{-2}$  power law the average column density in a 20'' beam would be larger by a factor 4 and 60 respectively. In summary, the beam-averaged ortho-H<sub>2</sub>D<sup>+</sup> column density in the cloudlets halo of NGC3198, if uniform, is predicted to range between  $\sim 10^9$  and  $\sim 10^{13} \text{ cm}^{-2}$ . If the halo is centrally condensed this number increases. For some cloudlet parameters used in the literature the emission will be optically thin, for others it will be optically thick. The two cases discussed above would suggest a ortho-H<sub>2</sub>D<sup>+</sup> column density around to  $\sim 10^{11} \text{ cm}^{-2}$  or less, if the halo is distributed uniformly. If a  $r^{-2}$  power law applies, the ortho-H<sub>2</sub>D<sup>+</sup> column density could be as high as  $\sim 4 \times 10^{12} \text{ cm}^{-2}$ .

At present, the rest frequency of ortho-H<sub>2</sub>D<sup>+</sup> at 372 GHz is observable with the CSO and APEX telescopes, and, for more distant galaxies, with JCMT, KOSMA and SMA. The line detectability depends somewhat on the telescope employed, but, based on previous published

observations, it is safe to say that present facilities allow detections of ortho- $\text{H}_2\text{D}^+$  column densities of about  $1 \times 10^{12} \text{ cm}^{-2}$  (Caselli et al. 2003; Ceccarelli et al. 2004). Much deeper integrations would lower this limit by about a factor 3, bringing the detectable ortho- $\text{H}_2\text{D}^+$  column density to  $3 \times 10^{11} \text{ cm}^{-2}$ . Therefore, we predict that the ortho- $\text{H}_2\text{D}^+$  372 GHz line should be detectable if the high end estimate of the  $\text{H}_2\text{D}^+$  abundance in cloudlets applies. Indeed, a positive detection of this line would not only definitively prove the presence of important amounts of cold molecular material in galaxies, but would also strongly constrain the location and nature of the cloudlets.

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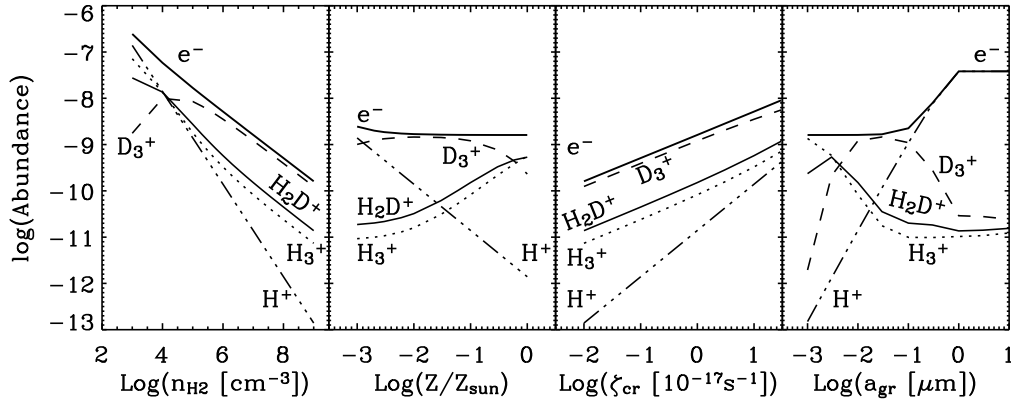


Fig. 1.— Predicted abundances of the main charge carriers in the dark halo cloudlets (based on the Ceccarelli & Dominik (2005) model). From left to right, the abundances are shown as a function of the gas density, metallicity, cosmic ray ionization rate and grain radius. When varying the metallicity, we reduced the standard abundances of dust grains, CO and  $\text{N}_2$  proportionally to the metallicity, relative to values typical in galactic molecular clouds:  $x(\text{CO}) = 9.5 \times 10^{-5}$ ,  $x(\text{N}_2) = 2 \times 10^{-5}$ , and a dust-to-gas mass-ratio of 0.01. The plots have been done for a temperature of 8 K, density  $10^7 \text{ cm}^{-3}$ , metallicity 0.1, cosmic ray ionization rate  $10^{-17} \text{ s}^{-1}$ , and grain radius of  $0.01 \mu\text{m}$  when these parameters are not varied in the relevant panel. The age of the clouds has been assumed larger than  $\sim 10^3 \text{ yr}$ , which is the timescale for the CO and  $\text{N}_2$  condensation onto the grains for a density of  $10^7 \text{ cm}^{-3}$  (the timescale scales with the inverse of the density).